"SWITCHING OF HIGH-POWER CURRENT PULSES UP TO 250kA AND SUBMILLISECOND DURATION USING NEW SILICON DEVICES - REVERSE SWITCHED DINISTORS."

Galakhov I.V., Gudov S.N., Kirillov G.A., Murugov V.M., Osin V.A., Zolotovski V.I.

Russian Federal Nuclear Center-VNIIEF
607190, Arzamas-16, Nizhni Novgorod Region, Russia

Chumakov G.N., Kovtun V.I., Martynenko V.A.
Saransk, Russia,

and

D.Larson

Lawrence Livermore National Laboratory
Livermore, CA, USA.

Abstract.

The switches based on silicon semiconductor devices - reverse switched dinistors are proposed to switch high-power pulsed currents of microsecond and submillisecond duration. The switch design is described for the operating voltage of up to 25kV and operating current of up to 200kA with the current pulses duration of 500 μs at $0.1I_{max}$.

We give the test results and estimate the possibility of using such a switch in the NIF capacitor bank.

Introduction.

There are many research areas in today's physics that address high current pulse switching problem. This problem is particularly topical for physics research installations associated with large-scale experiments. Thus, pulsed power systems for advanced high-power lasers (of about 1.0 MJ energy output) require development of a switch for current pulses up to 500 kA with submillisecond duration. Ignitrons and spark gaps have been used successfully in previous laser designs at lower currents, but will not operate at 500 kA. Therefore it is important to explore new switch designs and technologies.

Lifetime and reliability of high pulsed current switches are directly related to discharge plasma contraction phenomena. With the discharge being contracted into a narrow channel, electrodes erosion increases dramatically and shortens the switch lifetime, while erosion products depositing on the walls of discharge chamber cause prefire or other abnormal discharge behaviours, e.g. switch failure. Therefore, to achieve reliable high current switching, switch designs must be used which involve two distinct stages: volume discharge with the plasma filling the whole space between the electrodes, and contracted discharge with the plasma to be contracted into a narrow channel and the electrodes having their working area only partly used. The volume discharge stage determines performance rating of the switch. There are only two switch types like this that we know of: triggered vacuum switches and semiconductor switches. The most efficient triggered vacuum switches [1] have discharge contraction occurring at currents of 100 to 150 kA, and the opportunity for increasing this level is uncertain.

The semiconductor devices most commonly used in high-current switching applications are high-power thyristors. However, they have limited capabilities. The triggering mechanism is the major limitation to thyristor performance. A trigger current pulse applied to the control electrode generates a rather narrow plasma channel in the control electrode region which expands at the relatively slow rate of 0.005-0.1 mm/μs. The triggering process thus localized makes it difficult to quickly create a current-carrying channel of large cross-sectional area, so that thyristors cannot be used for switching pulsed currents comparable to those usually switched using gas-discharge devices. In the early 1980s, Ioffe Physics and Technology Institute (St.-Petersburg, Russia) designed and developed reverse switched dinistors (RSD), new semiconductor devices [2] that offered high-current switching performance substantially superior to thyristors and quite competitive with gas-discharge devices.

Report Documentation Page			Form Approved OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUL 1995	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Switching Of High-Power Current Pulses Up To 250ka And Submillisecond Duration Using New Silicon Devices- Reverse Switched Dinistors	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Russian Federal Nuclear Center-VNIIEF 607190, Arzamas-16, Nizhni Novgorod Region, Russia**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

The switches based on silicon semiconductor devices - reverse switched dinistors are proposed to switch high-power pulsed currents of microsecond and submillisecond duration. The switch design is described for the operating voltage of up to 25kV and operating current of up to 200kA with the current pulses duration of 500 f1S at O.llmax· We give the test results and estimate the possibility of using such a switch in the NIF capacitor bank.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Basically, current switching procedure in RSD is built around the idea to use an areally uniform plasma layer instead of the control electrode in a tyristor-type device. This would provide generation of a plasma channel of the same area as the silicon plate, and thus allow substantially higher pulsed current to be switched by the device. Reversed injection control was found to be the simplest and most efficient way to create this control plasma layer. Reverse injection produces a plasma layer via a short-term polarity change of the voltage applied to the device. Thus, RSDs are anode-controlled two- electrode devices.

The RSD-switched current is proportional to the silicon plate working area. With the development of 50 cm^2 RSD's, the range of switched currents could be extended to values previously switchable only by gas-discharge devices. Thus, ref.[2] describes test data on the assembly of three series connected RSDs of 50 cm^2 working area. This assembly had operating voltage up to 7.5 kV and switched square current pulses 100 μs duration and up to 300 kA high.

It was of interest to look at how 50 cm^2 RSD would behave in switching current pulses of submilliseconds' duration typical of pulsed power system of Nd-glass laser flashlamps, and what the critical current is where transition occurs from the volume to contracted discharge, the effect referred to in semiconductor technology as current lacing. This report describes early research data on this device.

Design of RSDs and RSD-based switches.

RSD design includes several tens of thousands of alternating transistor and tyristor sections positioned on a single silicon plate (see fig.1). The high-voltage p-n junction serving as collector for tyristor sections is common for all of them. Also common is the emitter n^+-p junction, which is to be broken down by the reversed-polarity control voltage pulse. The breakdown results in excess carrier charge being injected uniformly to the base regions of the structure, producing a control plasma layer over the entire surface of the structure.

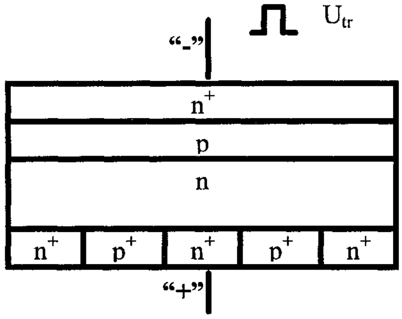

Fig.1. Scheme of RSD semiconductor structure,

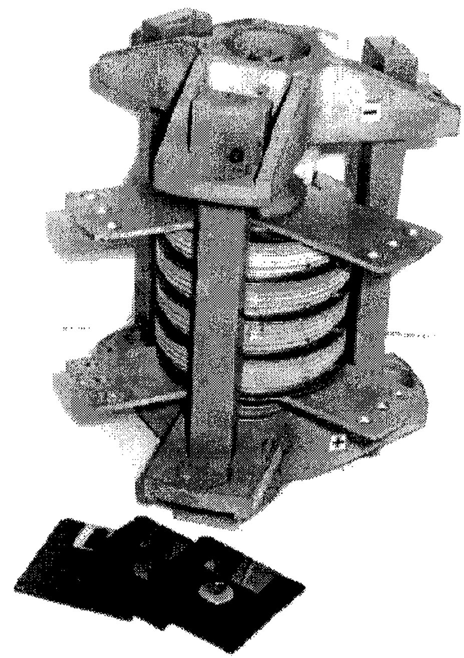

Fig.2. General view of 25 kV switch designated KRD-25.

With the anode control designed in RSDs, they can be easily assembled in series stacks for specified operating voltage without complicated transformer triggering circuits as required by similar thyristor assemblies. A stack of series connected RSDs only requires static voltage matching between individual units. These assemblies designed for 5 kV and 25 kV operating voltage have been made and tested. Fig.2 shows the general view of 25 kV switch designated KRD-25. This assembly includes 15 RSDs of 2 kV blocking voltage each, series connected and enclosed into a ceramic housing. The RSDs are designed like pellets, and some features are incorporated to provide close contacts between them. The force clamping RSDs in a stack should be significant. This is provided by suitable crossbars and spring washers. The housing also accommodates a resistance divider to match static RSD potentials.

Critical switched currents for 50 cm^2 RSD.

We can find the peak pulsed current the RSD is transmitting before its thermal breakdown by making use of single-pulse operation phenomenology [3]. According to this theory, critical switched current should be smaller than the value below, i.e.

$$I_m \langle K \frac{S}{f t_p^{1/3}},$$

where S is the RSD area in cm^2, t_p - current pulse duration (at the base) in seconds, f - current curve form-factor ranging in values from 1.0 for square pulses to 0.66 for half-sinusoidal, and K - coefficient controlled by RSD structure specifications.

The coefficient K is inversely proportional to the RSD base thickness that specifies the RSD operating voltage. K=210 for a 2 kV operating voltage. Thus, for a 50 cm^2 RSD and current pulses of 500 µs duration, the critical switched current will be expected to be 200 kA.

Note, that there are some restrictions on the applicability of this formula. Ref.[3] states that this theory has been developed for pulses within 100 µs duration. Submilliseconds' range may require accounting of comparatively slow processes not considered when this formula was deduced (e.g. heat diffusion effects), and thus may somewhat modify the resulting equation for maximum current. Nonetheless, this formula can be used to predict performance limits for RSD.

We have conducted experiments to test the performance limits of RSD of 50 cm^2 working area in switching current pulses of 500 µs duration at the base. The current pulse had shape as shown in fig.3. This shape represents flashlamp pulsed power in today's Nd-glass lasers. The testbench is schematically shown in fig.4. Testing techniques are similar to those described in ref.[4].

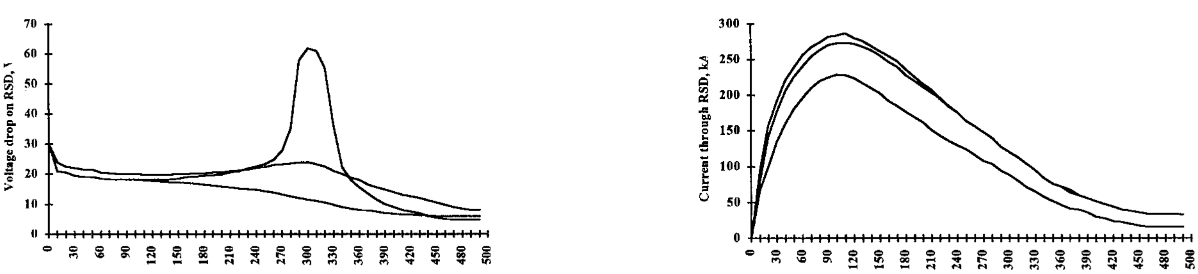

*Fig.3.*Typical shape of current and voltage drop pulses on RSD at tests.

Pulsed current was transmitted through the RSD, and its peak value was varied in the range between 100 and 300 kA by suitable variation of the capacitor bank charging voltage U_o, while the current pulse duration was kept unchanged. RSD triggering and main discharge events were separated in time using an additional switch K_1, with no voltage existing at RSD until the K_1 closure. This was done to keep the RSD triggering current unchanged in both peak value and pulse duration with charging voltage U_o variations of the basic switchable capacitance C_o, and also to ensure against the RSD structure heating by leakage currents associated with charging the capacitance C_o, and thereby, to allow the same initial conditions for its heating due to the C_o discharge current pulse. During the discharge, the RSD-switched current and RSD voltage drop were measured.

There were 17 RSD units of 50 cm^2 working area tested. Current lacing effect, or the discharge transition to contracted condition was indicated by the RSD voltage drop increasing dramatically at approximately 250 μs. Typical oscilloscope traces of RSD voltage versus time are shown for different switched current values in fig.3.

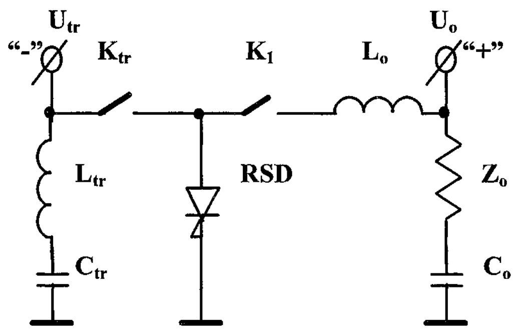

Fig.4. Testbench circuit for current tests.

For all the RSD tests, dynamic voltage steps were detected at currents at least 220 or 230 kA, moreover, 4 units had no voltage rise observed until 260 kA current. For two units, this voltage rise caused irreversible thermal breakdown of the structure (the currents were 230 to 250 kA). The remainder of units were still operating even following the voltage step indication of the device.

The testing techniques we used allowed us to evaluate the critical switched current for both individual RSD units and multiple series connected RSDs. We expected that heating conditions for RSDs at the ends of the assembly would be different from those towards the center, and this might result in lower maximum current switched by the assembly. As shown by the tests of two assemblies, one including three RSDs (for up to 6 kV operating voltage) and the other fifteen RSDs (for up to 30 kV operating voltage), no decrease in maximum switched current occurred in the assembly case.

Thus, we can assume that with current pulses of 500 μs duration at the base, the maximum switchable current value for 50 cm^2 RSD's is 250±10kA. For these currents, irreversible thermal breakdown in the RSD is probable as a result of current lacing. Currents up to 200 kA are considered safe for RSD's of this size. Note, that the above-given formula for maximum current yields a value approximately 20% lower than was observed.

<u>Critical charge value in RSD triggering. Typical triggering circuits.</u>

As mentioned above, for RSD triggering to occur, a current pulse must be transmitted through the RSD of the opposite polarity to the main discharge current. Moreover, excess carrier charge is injected into the base regions of the device, and this is what produces the control plasma layer. Uniformity of this plasma layer depends on the charge injected into the base, whose value at each point of the structure should exceed some critical level. When this requirement is met, the main discharge current will be uniformly distributed over the silicon plate.

The critical charge value depends on the process details of the device, and also steepness of the main discharge current (critical discharge is directly proportional to dI/dt [2]). We have evaluated the critical charge for the steepness of the main discharge current, equal to dI/dt=3 kA/μs, which is consistent with the current shape as shown in fig.3 (for I_{max}=250 kA). For this purpose we used the measurement technique for minimum switching losses, or energy loss in RSD switching. We conducted these tests using the testbench shown in fig.4. In so doing, we varied RSD triggering current characteristics to measure the voltage drop of RSD. With RSD triggering, there occurs an abrupt surge in voltage which is reduced in 1-3 μs to a fixed value. When the triggering current is decreased, the voltage surge increases in peak value, which is due to more energy dissipated in the RSD at switching (figs.5 and 6). Clearly, if the charge transmitted to RSD upon triggering (estimated as $Q_{tr} = \int_0^{t_{tr}} I_{tr}(t)dt$), is below 1.5 mC, the RSD voltage and loss will grow rapidly. Thus, for 50 cm^2 RSD's and 3 kA/μs main discharge current, the critical charge is 1.5 mC. For the RSD to show positive action, a charge of at least 10-15 mC should be delivered

by the trigger. It has been found experimentally that the critical charge value is not impacted by the series connection of several RSDs.

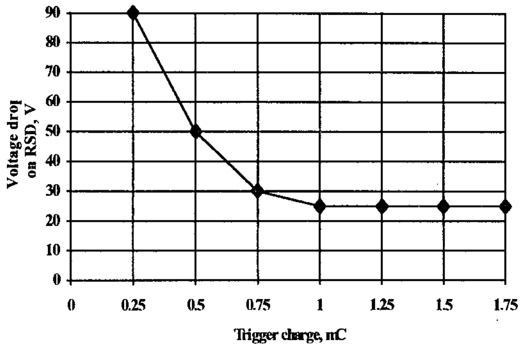

Fig.5. The curve of voltage drop on RSD at switching versus trigger charge.

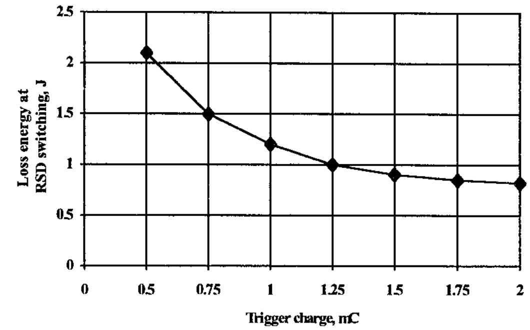

Fig 6. Energy dissipated in the RSD at switching versus trigger charge.

Several candidate circuits for RSD triggering have been tested. Essentially, the RSD triggering circuit accepted by many authors [2,4] implements time separation between RSD triggering events and the main discharge (fig.4) using a saturable choke rather than additional switch K_1. This isolation method is typical of two-electrode switches (see, e.q.[5]). We have explored the possibility of choke-free triggering of RSD. Large inductance in the main discharge circuit may allow this. Figs.7 and 8 show the diagram with and without an additional power supply in the control circuit. The diagram of fig.8 is suggested by the authors of ref.[4]. Its major disadvantage is numerous high-voltage components connected in parallel to RSD that will absorb all the main capacitor bank energy when a breakdown occurs. The RSD triggering circuit as shown in fig.7 was used for testing the assembly of 15 RSD (KRD-25). However, the circuit including choke isolation should provide more reliable RSD triggering.

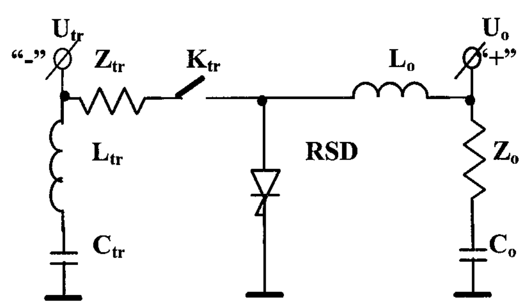

Fig.7. Diagram of the control circuit with additional power supply.

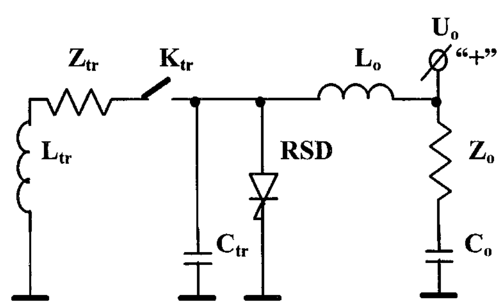

Fig.8. Diagram of the control circuit without additional power supply.

Conclusions.

Tests have been conducted for a new semiconductor switch based on 50 cm^2 reverse switched dynistors (RSD's), switching 250 kA peak, 500 μs (base width) current pulses. The critical current for this pulse duration was observed to be 250±10 kA. Exceeding this level may cause irreversable due to thermal breakdown in the RSD crystal structure. Operating currents of 200-220 kA may be considered appropriate for such devices. Prototype switches rated for 5 kV and 25 kV (i.e. assemblies of several series connected RSDs) have been tested successfully at these current levels.

The RSD voltage drop at these currents is 20 V or less, demonstrating promise for their use in assemblies of several parallel connected devices. Thus, RSDs offer attractive switch designs for operating currents as high as 400-500 kA, required by pulsed power systems for advanced high-power lasers, such as the National Ignition Facility.

RSD switch tests have shown that this switch technology promises to be useful in many applications requiring switching of high-current pulses in both microsecond and submillisecond ranges.

References.

1. Dethlefsen R., Sidorov V.A., Vozdvijenskii V.A. "Triggered Vacuum Switch Testing For Millisec Pulses"// Proc. 8th IEEE Inter.Pulsed Power Conf.- San Diego, June 1991, p.p.511-514.

2.Tuchkevich V.M., Grehov I.V."New technique of high power switching by semiconductor devices" L.,"Nauka", 1988.

3. Gorbatiuk A.V., Panaiotti I.E. "Dynamic overheat of RSD" Journal Tekhnicheskoi Fisiki, v.60, n.5, 1990, pp.129-135.

4. Grehov I.V., Korotkov S.V., Yakovchuk N.S. "Study of RSD in high current pulse modes" Elektrotechnika, n.3, 1986, pp.44-46.

5. Warren F.T., Bhasavanich D., Curry J., Hammon H.G., Hitchcock S., Naff J.T. //8th IEEE Inter.Pulsed Power Conf.- San Diego, June 1991, p.p.63-67.